AD-A055 211 ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT--ETC F/G 21/5
TECHNICAL EVALUATION REPORT ON THE MEETING OF THE PROPULSION AN--ETC(U)
MAR 78 R EGGEBRECHT, S LOMBARDO

UNCLASSIFIED AGARD-AR-116 NL

| OF |

AD
A055211

END
DATE
FILMED
7-78
DDC

AGARD-AR-116

AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

7 RUE ANCELLE 92200 NEUILLY SUR SEINE FRANCE

AGARD ADVISORY REPORT No. 116

Technical Evaluation Report on the 50th Meeting of the Propulsion and Energetics Panel A Symposium on High-Temperature Problems in Gas Turbine Engines

by

R.Eggebrecht and S.Lombardo

NORTH ATLANTIC TREATY ORGANIZATION

DISTRIBUTION AND AVAILABILITY ON BACK COVER

(14) AGARD-AR-116

NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

(11) Mar 78 (12) 20p.

(9)

AGARD Advisory Report No.116

(6)

TECHNICAL EVALUATION REPORT on the 50th Meeting of the PROPULSION AND ENERGETICS PANEL (50th)

A Symposium on HIGH-TEMPERATURE PROBLEMS IN GAS TURBINE ENGINES

by

(10)

R.Eggebrecht
MTU München GmbH
8000 München 50, Germany

and

S.Lombardo
Curtiss-Wright Corp.
Wood-Ridge, N.J., USA

CONTENTS

The Proceedings of the 50th Meeting of the Propulsion and Energetics Panel which was held in the Middle East Technical University, Ankara, Turkey, on 19–23 September, 1977 are published as AGARD Conference Proceedings CP-229.

A052 845

400 043

mt

THE MISSION OF AGARD

The mission of AGARD is to bring together the leading personalities of the NATO nations in the fields of science and technology relating to aerospace for the following purposes:

- Exchanging of scientific and technical information;
- Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;
- Improving the co-operation among member nations in aerospace research and development;
- Providing scientific and technical advice and assistance to the North Atlantic Military Committee in the field of aerospace research and development;
- Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field;
- Providing assistance to member nations for the purpose of increasing their scientific and technical potential;
- Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community.

The highest authority within AGARD is the National Delegates Board consisting of officially appointed senior representatives from each member nation. The mission of AGARD is carried out through the Panels which are composed of experts appointed by the National Delegates, the Consultant and Exchange Program and the Aerospace Applications Studies Program. The results of AGARD work are reported to the member nations and the NATO Authorities through the AGARD series of publications of which this is one.

Participation in AGARD activities is by invitation only and is normally limited to citizens of the NATO nations.

Published March 1978

ISBN 92-835-1277-4

Set and printed by Technical Editing and Reproduction Ltd
Harford House, 7–9 Charlotte St, London, W1P 1HD

TECHNICAL EVALUATION MEMORANDUM

The meeting was held at the Middle East Technical University, Ankara, Turkey, on 19–23 September 1977. 102 participants from nine NATO countries attended the technical sessions during which 37 papers from eight NATO countries (UK 11, US 7, FR 7, GE 5, BE 3, IT 2, NE 1, TU 1) were presented. Two more papers from Italy were made available for the Conference Proceedings (CP 229).

The aim of this Symposium was to review the main problems associated with the attainment of high temperatures in aircraft gas turbines and to assess the progress achieved since the last meeting within this subject area which was held in Florence, Italy, 1970 (PEP 36th Meeting).

The operating temperature, i.e., the temperature at the turbine inlet, has a major influence on the performance of turbojet engines. Increase in operating temperature reduces the fuel consumption and, at the same time, raises the thrust-to-weight ratio leading to a worthwhile reduction of frontal area and nacelle drag. However, a high operating temperature poses formidable problems in terms of component life and reliability, especially for the high turbine blade where failure may occur through oxydation, thermal fatigue, corrosion or creep. These problems are to be reduced by the development of new materials and protection coatings and by further advances of cooling techniques using air taken from the compressor.

Accordingly, the Symposium was arranged to include the broad variety of subjects in one introductory and survey session (I) and in seven other sessions specializing in Turbine Cooling Techniques (II), Combustors, Afterburners and Nozzles (III), Materials and Coatings (IV), Mechanical Problems (V), Effect of Cooling on Aerodynamic Performance (VI), Measuring Techniques (VII), and Prediction Methods (VIII).

In many of these areas, remarkable advances were achieved since the meeting in 1970. Amongst others the following conclusions were drawn by Messrs Eggebrecht and Lombardo who evaluated the Symposium:

– transpiration cooling of blades and vanes was shown to use small cooling air flow rates very effectively in keeping metal temperatures low. However, this benefit could be larger if the operating temperature of the appropriate porous materials could be raised further;

– cooling temperatures have reached the state where their application could change the performance of the component in question such that very small or even no net gain is resulting. In order to exploit the capabilities of advanced cooling techniques it seems to be necessary to fully understand the influence of cooling air injection methods as used in engines on turbine aerodynamics and overall engine performance;

– a considerable progress in fabrication technology for hot section components (film-cooled blades, diffusion-bonded transpiration-cooled blades and various coatings) has been demonstrated in several papers as compared to the last meeting in 1970;

– the primary interest in future development of combustor components will focus on liner cooling techniques, application of ceramic materials, improvement of analytical models for combustors, and engine design modifications due to the expected use of alternative fuels;

– though much progress has been demonstrated in achieving the performance benefits of advanced technology in small gas turbines, further efforts are required to come up to performance levels already reached in large engines.

The information exchange during and in addition to the technical sessions was very lively and proved to reach high standards resulting into further small-scale contacts and cooperative activities. It was noted with regret that the US engine industry could not participate to the extent originally expected.

Preceding Page Blank - NOT FILMED

TECHNICAL EVALUATION REPORT

by

R.Eggebrecht
MTU München GmbH
8000 München 50, Germany

and

S.Lombardo
Curtiss-Wright Corp.
Wood-Ridge, N.J., USA

1. INTRODUCTION

The 50th Meeting of the Propulsion and Energetics Panel of the NATO Advisory Group for Aerospace Research and Development was held at the Middle East Technical University in Ankara, Turkey, from 19 to 23 September, 1977. The purpose of the meeting was to review the status of the technology associated with the design and operation of gas turbines at high turbine inlet temperatures. The conference program was arranged by a committee under the chairmanship of Dr. D.K.Hennecke.

The timing of the meeting was most appropriate, since the last meeting devoted to high temperature turbines was the 36th PEP Meeting in Florence, Italy, in 1970. Since that time, much progress has been made in the understanding and the application of increased entry temperatures to both military and civil aircraft gas turbines.

The maximum cycle temperature at which today's aircraft gas turbines are designed to operate is increasing as rapidly as the technology of high temperature materials and cooling methods will allow. Increases in cycle operating temperatures result in higher specific output and increased cycle efficiency. From an aircraft systems point of view, the higher specific output raises the thrust-to-weight ratio of the engine, with significant reduction in engine frontal area and nacelle drag. Thus, the benefits of operating an aircraft gas turbine at increased cycle temperatures can be translated into additional payload or range or a combination of both. All modern aircraft, as well as industrial gas turbines, operate at cycle temperatures which require turbine vane and blade cooling, as well as special cooling configurations for other hot section components such as combustors, shrouds, discs, afterburners, etc. In conjunction with cooling, special considerations in materials and coating selections are required to insure the integrity of the design and reliable operation of these advanced engines. In this meeting, major emphasis was placed on the state-of-the-art of high cycle temperature gas turbines, with regard to heat transfer, performance and materials technology and their interrelationships. In addition, the meeting covered new developments under investigation which offer significant improvements in the performance, cost, efficiency and reliability aspects of advanced gas turbine engines.

The conference consisted of 39 papers adequately balanced in subject matter and between representatives from industry and government-sponsored organizations. The number of countries providing papers was nine, though specialists from other NATO countries were present and took an active part in the discussions.

The conference was divided into eight sessions dealing with the general theme of high temperature problems in gas turbine engines. It is apparent from the attached listing of these session titles and reference papers that the meeting covered a broad scope of activities relating to the high temperature aspects of gas turbines.

The following review and evaluation uses slightly different headings for comments on the papers presented and for emphasis of some features which are thought to have an important impact on future developments of high temperature turbines.

2. PROGRESS OF NEW RESEARCH AND DEVELOPMENT TEST FACILITIES

2.1 Static Cascade Rigs

Many of the data presented at the meeting dealt with test results from different cascade rigs, and the progress

made to convert these data into a form which would be useful to designers for predicting the performance and durability aspects of high temperature hot section components.

The present status of highly developed cooling technologies was only reached with the help of sophisticated laboratory cascade testing which allows detailed analysis of basic phenomena for comparison with, and further development of, theoretical methods. However, there is still a fundamental need to increase cooling effectiveness with a minimum of engine performance losses, while the engine manufacturer is resorting to the use of improved manufacturing methods, materials and coatings, which will offer further temperature potential. One can easily foresee that future research work will be faced with new and sometimes more complex cooling configurations for all the hot-end components of advanced gas turbines.

The very encouraging progress is worth noting which has been achieved using the so-called short-duration test facilities at Oxford University, VKI and MIT reported during this meeting by D.L.Schultz (31)*, B.E.Richards (34) and J.F.Louis (28). The tests can be performed at actual engine Reynolds and Mach numbers and actual gas-to-wall temperature ratios. Heat transfer measurements are made by highly developed thin-film techniques, and fast data acquisition systems are available for recording and subsequent processing of transient data.

Interesting cascade testing with measurements of heat transfer along a PVD blade profile has been reported by B.W.Martin (32) from Wales University. These tests also employed a transient method by measuring temperature – time responses of blade surface thermocouples when the blade was suddenly introduced into a heated air stream.

One of the key problems in cascade testing, whether in the steady-state or transient mode, is the proper simulation of environmental conditions prevailing under actual engine conditions and influencing, for instance, the cooling performance of vanes, blades, shrouds and combustor liners. F.J.Bayley (37) stated the present position very clearly, when he pointed out that even the relevant characteristics of the engine flow are not yet definable, not to mention simulation under laboratory conditions. H.Köhler (6) in his paper compared surface temperature measurements and associated heat transfer coefficients from static cascade tests with results on a comparable rotor blade operated in an engine at similar Reynolds and Mach numbers and with the same gas-to-wall temperature ratio. The large discrepancies observed, mainly on the leading edge and pressure surface, highlight the possible effects of engine-related environmental conditions, such as main-stream turbulence originating from unsteady combustion, cooling air admixture and periodic velocity oscillations due to blade wakes.

For investigation of some separate effects of turbulence, F.J. Bayley (37) presented a new experimental set-up at Sussex University consisting of a static cascade with an upstream turbulence generator which was conceived as a rotating squirrel cage. This device allows the investigator to vary the turbulence intensity by using a range of bar diameters and to vary the frequency of velocity fluctuations through the rotational speed. The experiments he reported about were mainly done in the range of up to 6 kHz with measured velocity fluctuations in the range of 24% to 48% turbulence and showed some dramatic effect on local and mean blade profile heat transfer coefficients.

There was general agreement among the speakers that the data obtained from the above described laboratory tests are very useful and necessary for the design of hot-section components.

2.2 Turbine Aerodynamic Rigs and High Temperature Turbine Testing

For investigation of the effect of coolant injection on turbine aerodynamics, cold or warm air turbine rigs are commonly used, as referred to in papers by J.D.McDonel (29) and H.F.Due (4). As reported by A.W.H.Morris (12) at NGTE, a high-temperature single-stage research turbine has been used for recent testing of transpiration-cooled NGV's at design conditions of 1650 K gas temperature and 4.5 bar inlet pressure.

W.Kühl (7) described temperature measurements on rotating turbine blades in a single-stage test turbine at the Technische Hochschule, Aachen, which were aimed at analysing blade-profile heat transfer under moderate turbine inlet temperature and pressure conditions up to 1173 K and 1.5 bar respectively.

A major new test facility presented during this conference in the papers by J.Francois (5) and Y.Le Bot (33) is the so-called French MINOS (Montage inter ONERA-SNECMA) operated at CEPr, Saclay.

This test facility is basically a high-temperature test turbine with an upstream engine combustor, in which an attempt is made to simulate engine environmental conditions with respect to the combustor-turbine unit. The max. designed operating temperature is 1800 K and the max. entry pressure delivered from the plant feed system is 4.5 bar.

The authors (5) quote an impressive program of future investigations covering a broad range of high-temperature turbine problems including

– turbine aerodynamics
– various heat transfer and film cooling investigations on NGV's, rotor blades, casings and end walls

* Number in parentheses refers to the Paper in the main Conference Proceedings.

– thermal fatigue tests by means of cyclic variation of cooling air flows
– testing of abradable materials with respect to improvements in running clearances and reduced air leakages.

There is no doubt that each of these problem areas represents a major aspect in the development of advanced turbines. The ambitious targeting for this test facility essentially requires advanced measuring techniques, which are described in the paper by Y.Le Bot (33):

Total pressure and temperature probes designed for fast dynamic response and capable of operating under high temperatures have, for instance, been developed for measuring turbulence at turbine entry, and for analysing rotor downstream wakes. Laser anemometry is seen to be not yet ready for this application. Blade temperatures are being measured by embedded thermocouples and optical pyrometers. For heat transfer analysis on turbine blades, a transient technique involving sudden cooling air flow shut-off is being employed. Heat flux measurements on turbine casing liners can be performed with fluxmeters developed by SNIAS. For tracing cooling air flow paths and evaluating film cooling effectiveness, using the analogy between heat and mass transfer, the rig is designed to allow gas sampling with chromatographic analysis of gas concentrations.

It must be realized that the extent of the instrumentation used causes some changes in comparison with the actual engine situation such as, for instance, wider spacing between blade rows. Another limitation which must be recognized is the rather low operating pressure of the combustor, whose outlet conditions may alter in the actual core engine situation. This comment underlines the author's opinion that MINOS will at least help to bridge the gap between classical component rig testing and experimental investigations under real engine environmental conditions.

From the measurements already made and described in these two papers, it is evident that MINOS has the capability to make a major contribution to solving future high-temperature turbine research and development problems.

3. COOLING TECHNIQUES AND HEAT TRANSFER INVESTIGATIONS

3.1 Recent Work on Convection-Cooled Turbine Blades

Blade cooling is commonly used in present military and civil engines. However, surprisingly little information is available about the local gas-side and cooling-side heat transfer rate for different blade profiles and internal coolant passage configurations under actual engine operating conditions. In order to distinguish the physical phenomena occurring under these conditions, there is still a fundamental need for heat transfer investigations on cascades and research turbines, as reported on by several authors at this conference. The following table summarizes experimental and/or theoretical work devoted to external turbine blade heat transfer in the absence of boundary layer coolant injection.

Author/Ref.	Paper	Investigation Performed	Varied Parameters	Comments
J.F.Louis	(28)	profile heat transfer distribution (p.h.t.d.) for four transonic blade profiles	outlet Mach number; incidence angle	shock tunnel cascade rig
D.L.Schultz	(31)	p.h.t.d. for a high pressure turbine blade	outlet Reynolds number; Tu level	short-duration wind tunnel operating with single-stroke light piston compression
B.W.Martin	(32)	p.h.t.d. for PVD* turbine profile	outlet Mach and Reynolds numbers; Tu level	blades are shifted into hot gas duct and undergo transient heating
F.J.Bayley	(37)	p.h.t.d. for high pressure turbine rotor blade	outlet Mach and Reynolds numbers; Tu level and frequency	steady state cascade tests with upstream squirrel cage turbulence generator
W.Kühl	(7)	p.h.t.d. for turbine blade and cooling effectiveness	cooling air mass flow	test turbine with slip ring equipment
H.Köhler	(6)	p.h.t.d. and cooling effectiveness for four cooling configurations with unchanged outer blade profile	mainly outlet Reynolds number and cooling air mass flow	steady state cascade tests and engine measurements on rotor blades by means of thermal paints
J.Francois Y.Le Bot	(5) (33)	p.h.t.d. for internally cooled NGV behind combustor	no parameter variation reported	high temperature turbine rig "MINOS"

A review paper using these newly provided heat transfer data for comparison with previously published results by other authors appears to be very desirable. From the amount of available data one could expect that some fruitful incentives for improvements in heat transfer prediction by means of boundary layer theory may arise.

* Prescribed velocity distribution.

One paper, presented by W.D.Morris (38), dealt with heat transfer in rotating coolant channels as affected by Coriolis forces and rotational buoyancy. It turns out that the use of forced convection data obtained with stationary tubes for the prediction of heat transfer in rotating tubes can lead to significant errors of either over- or under-estimations. On the basis of the already available test results of this research work, which has just started, it seems advisable for blade cooling design engineers to closely watch the further outcome of these investigations.

Turbine blade cooling by means of a closed thermosyphon system would offer the advantage of high internal heat transfer coefficients. The paper by R.W.Stuart Mitchell (13) presented new experimental investigations for the stationary vertical, the stationary inclined, and the rotating closed thermosyphon, with water and mercury as working fluid, and gave dimensionless correlations of the measurements. The results suggest that, in addition to the commonly used Grashof number based on gravity acceleration, a dimensionless centrifugal acceleration term also has a marked influence on the Nusselt number of the cylindrical tube under investigation.

3.2 Film Cooling of Hot-End Components

An analysis of film cooling physics for any practical design of turbine blades, end wall elements, stators or combustor and afterburner liners is not yet feasible.

No wonder that an increasing amount of research work is being done. The following table gives a survey of film cooling work reported on.

Author/Ref.	Paper	Configurations	Range of Thermodyn. Parameters	Comments
J.F.Louis	(28)	angular injections for flat plate streamwise angles 10°, 20°, 30°, crosswise angles 0°, 30°, 50°, 70°, 90°	Ma_0 = 0,5 T_0 = 556 K T_c = 122 . . . 278 K $\dot{m}$ = 0,1 . . . 1,6	shock tunnel with about 10 ms steady flow test time $\dot{m} = \frac{\rho_c W_c}{\rho_o W_c}$
		blade profile with various film-cooling ejections	exit Mach number = 0,6 T_0 = 450 K T_c = 293 K	
B.E.Richards	(34)	flat plate with injection through double row of holes with 30° stream-wise injection angle	Ma_0 = 0,6 T_0 = 382 K T_c = 267 . . . 365 K $\dot{m}$ = 0,5 . . . 1,5	short duration wind tunnel operating with single-stroke light piston compression
J.Francois	(5)	turbine casing; end wall "MINOS" turbine rig conditions		
H.Kruse	(8)	turbine blade leading edge film cooling flat plate	T_0 = 400 K T_c = 293 K $\dot{m}$ = 0,5 . . . 2,0	single blade model tests
R.Best	(17)	slot configuration inside tube	Ma_0 = 0,1 . . . 0,16 T_0 = 453 . . . 500 K T_c = 293 K W_c/W_0 = 0,5 . . . 1,9	variation of coolant side Tu
E.Le Grives	(36)	single and multiple row of holes with various stream-wise and crosswise angles	wide range of blowing parameter; thermo-dynamic data not all given explicitly	flat plate experiments; comparison of test results with new analytical prediction method presented by the author

J.F.Louis (28) reported about a very comprehensive experimental program performed at MIT on film-cooling configurations mainly of single and double line holes for different streamwise and crosswise angular injection. The importance of these experiments becomes clear when it is considered that most of the practical application in turbines make use of injection holes rather than continuous blowing out of slots. Substantial research work on film cooling with various injection hole configurations was performed about one decade ago at the University of Minnesota, as reported by E.R.G.Eckert at the 1970 AGARD PEP Meeting, and at Arizona State University by D.E.Metzger et al. These investigations were made for very low mainstream Mach numbers and in some cases in the transonic range. The temperature ratio between coolant and mainstream was close to 1.0. At the same conference C.Liess reported about measurements at VKI downstream of inclined injection holes which were taken at elevated Mach numbers of 0,4 . . . 0,6 but still with only small temperature differences. The present shock tunnel tests at MIT cover nearly the full range of thermodynamic parameters which occur in advanced turbines. The overall correlation used is essentially based on equivalent slot width, the square root of momentum ratio to the 1.35th power and the coolant Reynolds number to the 0.25th power. It must be noted that this correlation describes fairly well the experimental results of individual injection hole arrangements. However, the attempt to describe the isothermal efficiencies of the very different geometric configurations by such an overall correlation parameter leads to a rather wide scatter of data and therefore

is still unsatisfactory. It is interesting to note that Louis can align the effectiveness of hole and slot configurations by a simple geometric "mixing area" correction.

The very high potential of presently available test equipment becomes evident from the presentation by D.L.Schultz (31) and D.E.Richards (34) on tests with the so-called Isentropic Piston Tunnel at Oxford and VKI, respectively. Film cooling experiments using a double row of holes with a 30° injection angle were reported on by Richards. The test results show similar trends to the previous investigations by Eriksen and Goldstein, which were performed under incompressible flow conditions. So far, the results indicate that there is obviously no strong influence of increased Mach numbers. It must be borne in mind, however, that primarily, these tests should prove experimentally the linear relationship between "overall heat transfer coefficient" (based on difference of mainstream and wall temperature) and a non-dimensional coolant temperature. Furthermore, of course, Richards demonstrates the capabilities of the transient test technique based on single-stroke isentropic compression rather than performs any systematic study on film cooling configurations.

As far as continuous blowing is concerned some different analytical methods are already available. In his paper J.F.Louis (28) refers to Demirjian, whose mathematical modelling for angular injection predicts quite well the film behavior in the region near the slot injection and up to blowing rates at which boundary layer lift off occurs and consequently the cooling effectiveness is reduced.

For injection through discrete holes, a new analytical technique was presented by E.Le Grives (36). It must be appreciated that this paper already demonstrates impressive progress in theoretical methods for describing interaction between mainstream and single jets and array of jets by means of the dilution theory. The paper provides valuable references to previous publications by other authors and points out that the future work of the authors will be focussed on curvature effects.

Generally speaking, more fundamental experimental data are obviously needed in order to develop computational methods for the highly complex three-dimensional flow situation in the case of film cooling with hole injection configurations which are aimed at improved cooling effectiveness. Furthermore, this future work will have to simulate more closely engine environmental conditions, in order to study the effect of hot gas mainstream flow characteristics prevailing in turbines behind engine combustors.

In his paper (17) R.Best draws attention to the velocity profiles and turbulence distribution of the coolant flow in the plane just before entering the mainstream boundary layer, which he measured for different slot widths and for a wide range of blowing rates. He shows that there is an adverse effect of the entering coolant turbulence upon film cooling effectiveness. This effect is more pronounced for coolant to mainstream velocity ratios $W_c/W_0 = 1$. His semi-empirical model fairly well describes the observed experimental phenomena of this type of tangential slot film cooling.

Rather little is known about the interaction of film cooling jets with the mainstream boundary layers of turbine blade or vane leading edges, which have to withstand the highest thermal loading. H.Kruse (8) reported about boundary layer measurements using a minature temperature probe in the vicinity of a turbine blade leading edge simulated by a single airfoil mounted in a small tunnel with adjustable flexible walls. From these investigations, it becomes evident that, for differently angled injection hole arrangements, there is a strong influence of the coolant blowing rate upon the local cooling effectiveness. Furthermore, it is shown that any changes in the stagnation point severely affect the cooling performance when there is only one row of holes near the leading edge.

3.3 Transpiration Cooling

L.S.Han (11) presented a paper on the analytical studies being conducted at Ohio State University on the influence of transpiration cooling on turbine blade boundary layers. The authors described a method by which the external boundary layer and heat transfer distribution can be calculated.

The experimental and theoretical work by F.J.Bayley (10) reported on at this meeting confirmed again the very high cooling effectiveness of transpiration cooled turbine vanes and blades compared with other cooled blade configurations. He also pointed out the excellent correlation of the heat transfer aspects pertaining to the design of transpiration cooled components. In his paper A.W.H.Morris (12) reported on the experimental evaluation of a transpiration cooled nozzle guide vane. The test program was conducted to evaluate the thermal design of the NGV and to determine the influence of the transpiring flow on stage efficiency. Cascade tests and a single stage high temperature turbine test rig were utilized in this program. The vanes used in this evaluation consist of a POROLOY porous metal airfoil, diffusion bonded to the main structural element. The cascade and engine test results demonstrated again the uniformity in airfoil metal temperatures and the high effectiveness of transpiration cooled blades and vanes. On the mechanical aspects of transpiration air cooled blades, the authors, on the basis of the single stage rig tests, conclude that the uniformity in airfoil metal temperatures possible with transpiration cooled blades and vanes will result in reduced thermal stresses and propensity to thermal cracking. Their test results lead them to believe that pore blockage of the transpiration cooled airfoil structure is not a significant problem. In addition, inadvertent exposure of the turbine to foreign object damage showed extensive maltreatment of the transpiration cooled blades could be tolerated without disastrous consequences. All the above mechanical characteristics of transpiration cooled blades, confirm the test

results noted earlier by another author and presented at the 36th PEP Meeting in Florence, Italy, in 1970. In noting the quality of the transpiration cooled vanes of the current paper and the quality of the vanes of the earlier reported work, it is obvious that significant strides have been made, over the past seven years, on the fabrication aspects of transpiration cooled structures.

As regards the performance aspects, the authors presented cascade data on profile loss coefficient versus coolant flow ratios on fully transpiration cooled nozzle guide vanes (NGV), as well as for transpiration air cooled vanes with various percentages of the suction surface blocked. Using these data and test results from the testing of the vanes in a single stage turbine test rig, the authors then conducted engine cycle studies comparing the sfc and thrust relationships of a transpiration cooled NGV configuration with a conventionally cooled NGV. On the basis of this study, the authors concluded that direct substitution of transpiration cooled NGV offered no significant performance advantages over the higher coolant flow usage of a conventionally cooled NGV turbine stage. In their assessment of turbine efficiency when using transpiration air cooled NGV's the authors, in applying their cascade results to the cycle studies, have defined turbine efficiency according to the method outlined by L.Y.Goldman of NASA. Consequently, the derived turbine-stage thermodynamic efficiency decreases markedly with increasing coolant flow. The simple application of this efficiency correlation on engine cycle studies, however, appears to be inconsistent with the findings of other investigators. Additional research and engine development testing is indicated to clarify the situation.

3.4 Rotating Disc Heat Transfer

In order to meet the requirements of advanced analytical techniques in the structural design of compressor and turbine discs, improved prediction methods for steady-state and transient temperature distributions are necessary. The solution of the basic heat-conduction equations for any geometrical configuration appears to be no longer a problem and several mathematical routines are available which tend to use effective finite-element methods. This was also indicated in the paper by M.Caprili (39). It gives, however, details of a different mathematical approach to disc temperature calculation in the case of prescribed surface heat transfer coefficients. Furthermore, the paper demonstrates, in a parametric study, the effect of disc heat transfer coefficient and coolant mass flow on radial temperature distributions in a typical turbine disc.

In a general comment, it must be stated that, for several rotating disc arrangements, the analytical methods for calculation of the heat transfer boundary conditions are often based on rough empirical methods. It can be said that past progress in this field of heat transfer research has not kept pace with fast heat conduction solution procedures which are nowadays being widely used. Therefore, it must be appreciated that one paper by J.M.Owen (14) was devoted solely to the very problem of heat transfer from turbine and compressor discs. Whereas several previous publications have already dealt with different rotating disc and cavity arrangements, this paper in particular presents heat transfer measurements for

(a) the situation of central axial throughflow and

(b) the situation of radial outflow of coolant

between co-rotating discs.

The experiments reveal strong vortex breakdowns for the situation (a) and identify different heat transfer regimes for the situation (b). Judging from the present results, the author's concluding view must be shared that much more research work is necessary for establishing theoretical or even empirical prediction methods.

4. EFFECT OF TURBINE COOLING ON AERODYNAMIC PERFORMANCE

From the angle of aerodynamic losses, the most attractive blade profile position for ejection of cooling air is seen to be the trailing edge of the blade. O.Lawaczeck (30) presented cascade wake flow measurements in a wide range of downstream subsonic to supersonic flow conditions. The experimental results provide basic turbine design data in terms of downstream flow angles and loss coefficients for this type of coolant ejection.

The evaluation of the effects of film-cooled vanes and blades on turbine aerodynamic performance and the effect on overall cycle thermodynamic efficiency was the subject of the paper presented by J.D.McDonel (29). The testing was done on a single-stage turbine test rig which featured five independent coolant supplies for independent variations of coolant-to-mainstream temperature ratios, pressure ratios, and mass flow ratios. The program included five test configurations, including two different film cooling designs, and three combinations of film-cooled and solid airfoils. Test results were presented showing the effects of the individual and combined vane and blade cooling air flow ratios on overall stage efficiency. These results were then compared with previously reported analytical methods, and the correlation was quite good. Using the results of the turbine rig, McDonel conducted a cycle analysis study program on a typical high temperature high-performance core engine to demonstrate the effects of cooling air utilization on overall engine performance. The base line turbine inlet temperature of the core engine was 1478 K (2200° F).

The results of this study were presented in parametric form, showing how engine output and efficiency varied with cooling air flow usage for various increases in turbine inlet temperature. This paper clearly demonstrates the potential cycle performance gains resulting from increases in engine cycle temperatures. In addition, it also points out

that, if the cooling is inefficient, the increased coolant flow rates and film injection losses can erode the potential cycle performance gains very rapidly. Curves were presented which showed specific limits which must be placed on the coolant flow rate for specific temperature increases. These results should be helpful to designers in establishing coolant flow limits during engine preliminary design studies. This paper was most timely, since film cooling of vanes and blades is now well established in modern aircraft engines.

Small turbines are generally accepted "to be different" and to have their own problems. During the last 10 to 15 years the small, cooled, axial-flow turbine has been the subject of several research programs. H.F.Due (4) presented a very useful review paper on the special aspect of the aerodynamic performance of the small turbine. The author presented several experimental results of various US-industry and government-sponsored investigations and concluded that considerable efforts are still necessary in order to improve turbine design methods, with special emphasis on prediction of coolant effects.

Besides the author's statement, it is believed that the expected better understanding of aerodynamic losses will guide new approaches to cooled turbine designs which offer still further potential for reduction of losses owing to adverse interaction between turbine mainflow and discharging cooling air.

5. COMBUSTORS AND AFTERBURNERS

Investigation of different liner cooling configurations of combustors and afterburners of aero engines was the general subject of the paper presented by M.Buisson (15). It presents rig measurements of cooling effectiveness by means of the gas analysis technique and the application of thermal paints and outlines the basic features of a simplified analytical approach which is being used for predicting the wall temperature of combustors and afterburners. Furthermore, the advantage of combustor liner sandwich design, which employs effective convection cooling before coolant ejection takes place, is emphasized.

J.Winter (16) discussed various practical solutions for combustor cooling problems typically associated with a reverse-flow annular combustor and with a cylindrical flame tube combustor operating in a regenerative gas turbine engine. This paper is mostly devoted to the very typical development problems combustion engineers are faced with, when component life has to be increased or more potential for engine uprating is necessary. The subject of this paper is seen to be very suitably placed in this "High Temperature Problems" conference, the intention of which is, on the one hand, to cover the wide scope of present scientific research work and, on the other hand, to deal with application problems which influence the direction of future research work.

A topical area of combustor-related research work is the development of analytical models which describe exhaust species concentrations as well as overall combustor performance. The paper of W.P.Jones (40) et al., presented by C.H.Priddin, dealt with measurements of species concentrations and velocities in a small-scale research combustor, these being compared with predictions of their mathematical model of chemically reacting flow which uses finite-difference equations. The present status of this model describes the profiles of fuel/air ratios and UHC concentrations quite well, but exhibits shortcomings in the prediction of CO concentrations along the combustor axis. The authors discuss possible approaches to overcome the present limitations in future developments in the model. Without doubt, some of these improvements can be easily incorporated into the existing mathematics as, for instance, a modified probability function or an additional reaction mechanism for NOX formation.

The authors regard the introduction of adequately prepared fuel breakdown physics, with model capabilities to describe ignition and extinction limits, as a rather more longterm development. Hesitation may, therefore, be justified in sharing the optimism expressed in the authors' concluding statements which suggest that only a little further development is necessary.

Alternative aviation fuels under consideration for future aircraft engines will influence especially the combustor system design. The paper by L.Martorano (18) deals with H_2-air combustion in a coaxial-stream cylindrical combustor up stream of a small single-stage research turbine featuring variable nozzle guide vanes.

The primary zone air loading of the combustor can be varied by movable inlet baffles and testing has been done over a wide range of fuel/air ratios, but no specific details of combustor measurements are given. It can be expected that the impact of alternative fuels on engine combustor design, as well as on cooling techniques, will attract increasing interest in future high temperature turbines. In this sense, the subject of this paper is believed to be also of considerable importance for future High Temperature conferences.

The last paper of the combustion session was devoted to the severe problem of low-frequency combustion in mixed-flow afterburners known as rumble or chugging. F.N.Underwood (19) categorised the several possible mechanisms which are normally seen to cause or regulate this special phenomenon. The paper gives a status report on a research project which is aimed at developing a reliable empirical and analytical model to aid afterburner design.

The experimental rig test data presented identify airflow dynamics and fuel distribution as main rumble contributors and the overall mathematical model of the augmentor system is shown to already predict typical rumble conditions.

Improvements by incorporation of a more adequate combustion model are necessary and were announced by the author.

6. HIGH TEMPERATURE MATERIALS AND COATINGS

Six papers were given, discussing the properties, characteristics, and selection of materials for use in hot section components operating at high turbine inlet temperatures. G.M.Ault (3) presented a very comprehensive survey on the status, progress, and future potential of advanced processes, materials, and coatings currently under development by the gas turbine community for advanced high temperature engines. As noted in previous papers (12, 29), significant payoff in engine performance can be achieved by minimizing the amount of cooling air used. Thus, the development of advanced materials and coatings, together with the development of improved cooling techniques are keys to realizing the full performance benefits of the high temperature gas turbine. In his paper, Ault (3) also predicted that pre-alloyed, powder-metallurgy-processed super alloys will afford increased strength and fabrication cost benefits, especially for turbine discs. Oxide dispersion strengthened alloys for use in vanes and combustor components show at least 90°C (160°F) higher use temperature potential than conventional sheet materials. Ceramics offer the highest use potential, in the order of 1400°C (2600°F), of all materials. Good progress in solving some of the problems inherent in ceramic components is reported on SiC and SiN_4 materials. Directional structures offer a major improvement potential over the best conventionally cast super alloys. D.S. eutectic alloys appear to offer as much as 80°C (150°F) use temperature advantage. Refractory fiber-reinforced super alloys afford potentially the highest use temperature capability of current super alloys. The advances in the development of more effective coatings for advanced super alloys were presented, comparing the effectiveness of aluminide coatings with the more advanced PVD, Co, Cr, Al, Y, aluminized Ni, Cr, Al, Si and the Pt-Al systems. Tailoring the coating to the substrate is vital for optimum effectiveness. Such tailoring can most readily be achieved with the PVD* process. Insulating refractory coatings show potential in providing an effective thermal barrier on blades and vanes. Ceramic coatings in the order of 0.25 mm (.010 in.) thick on a typical core engine study showed an eightfold reduction in cooling air flow and a 110°C (220°F) reduction in vane metal temperatures. Furthermore, the predictions are that a thermal-barrier-coated, convection cooled blade would be as effective as a full coverage film cooled blade in view of the reduced aerodynamic losses. Naturally, many problems involving cost, fabrication, and material property characteristics must be solved before these advanced materials and concepts can be used in the hot section of engines.

In outlining the trends toward improved high temperature materials, Ault (3) also stressed the potential improvements in material properties afforded by directionally solidified composites. H.Bibring (20) reviewed the progress of the ONERA developed family of refractory D.S. materials. Material properties of COTAC 74 are compared with similar properties of IN 100 material, showing the improved high temperature characteristics of the COTAC 74 over IN 100 material in the 1000 K metal operating temperature range. For increased corrosion protection, COTAC 74 can be protected by the coating DE 77 presented by Ph. Galmiche (22). Progress on the development of COTAC 74 has been sufficient to justify testing blades in an actual engine. On the basis of the work done so far, the authors claim that the increased temperature properties of COTAC 74 can be immediately exploited in the field of uncooled turbine configurations. However, more development efforts are required to apply this material to air-cooled blade configurations.

A very interesting paper was presented by A.D.Davin (23) on the development and experience of overlay coatings for the protection of cobalt-based alloys from hot corrosion. He points out the limitation of diffusion-type coatings in providing good oxidation protection, but stated these coatings lack the ability to adequately control sulphidation or hot corrosion. Furthermore, diffusion coatings applied to directionally solidified or oxide-dispersion-strengthened metals may alter the alloy properties. The overlay coatings, of the Co/Ni Cr-Al-Y type, eliminate most of the disadvantages of the diffusion coatings, and have shown exceptional corrosion resistance in service. The Co/Ni-base overlay coatings were shown to provide increased protection from oxidation and corrosion in high temperature turbine applications. The individual constituents of the overlay alloy can be optimized as a function of ductility requirements or coating process.

The prediction of the corrosion behavior of super alloys exposed to combustion gases is a very difficult task. The paper by U.Ducati (21) deals with the effects of sulphates, chlorines, and mixtures of them on the corrosion behavior of typical commercial nickel super alloys. In addition, some experimental alloys and a Co-base super alloy, together with a few typical impregnation coatings are reported on. The results of this work confirm the observation of Billingham (1973) on the influence of thermal treatment on corrosion behavior of super alloys; the hypothesis of intervention of electrochemical steps in hot corrosion has been advanced and justified.

The evaluation of a ceramic combustion chamber for a small gas turbine engine was the subject of G.Sedgwick's paper (27). The combustor was fabricated from hot pressed silicon nitride and flame sprayed reaction bonded silicon nitrate. The design of the combustor was tailored to take account of the lack of ductility of the ceramic material, by utilizing stacked rings for the flame tube and a low stressed reverse flow disk. Twelve ceramic components were utilized in making up the combustor assembly. Combustion testing in excess of 1200 K (2250°F) turbine inlet temperature was accomplished. Seven of the components survived the seven combustion tests of approximately 5 hours' duration. The greatest number of failures occurred on the two most complex components, namely the head

* Physical vapour deposition.

plate and rear disc. The failures of these components continued even after redesign to very low stress levels, and indications were that a major contributing factor was material inhomogenity.

Ph. Galmiche (22) presented a very informative paper on the ONERA developed coating process, which permits the application of a pack coating on both the external and internal surfaces of the blades and vanes. Mr. Galmiche presented micro-photographs of the wide application of this new coating process to conventional super alloys, as well as to advanced D.S. alloys such as COTAC 74 previously described by Bibring (20). Especially interesting were the results of the DE 77 coating applied to COTAC-74 D.S. material, which showed no distress after 500 hours of cyclic testing to 1130°C (2070°F). The coating method is applicable to new parts, as well as to parts which have been previously coated by thermochemical, chemical or PVD methods. This latter point is important from a maintenance standpoint, since blades which show coating distress during the overhaul process may be reprocessed by this coating technique.

7. REMARKS ON OVERALL ENGINE DESIGN AND PERFORMANCE ASPECTS

Two papers were addressed to some overall engine aspects as seen from the engine manufacturer's point of view. The paper presented by J.L.Price (24) dealt with different structure technology advancement areas that are dictated by the current trend of high thrust-to-weight engines. Furthermore, the author described details of a systematic time-phased development plan, which included the implementation of a sophisticated computerized structural analysis method. Mission-related stress analysis of static and rotating components and tip clearance control of rotor blades, for instance, are covered as important problem areas for advanced engines, and prospects are given for expected trends of major turbine design parameters over the next decade.

The paper presented by E.A.White and M.J.Holland (1) dealt with the influence of aircraft engine mission profile and engine rating on the service life of air-cooled high pressure turbine rotor blades, in particular. This paper also illustrated computerized analytical techniques available for assessment of critical engine components with respect to their life consumption. The authors presented some interesting results of a parametric study for a military aircraft engine operating with an assumed 1600 to 1800 K turbine stator outlet temperature. Some specific problems of small turbine technology were mentioned by Belaygue (2) who addressed also some aspects of overall engine performance with respect to increasing turbine temperatures.

Although these papers gave some trends of turbine design requirements, it is unfortunate that, generally, fairly little data was presented on the overall engine performance aspects, both theoretical and practical, of high temperature gas turbines. It is understandable that the engine manufacturers are reluctant to discuss the overall status of, and experience with, their current or advanced high temperature engines, because of commercial or proprietory considerations. Nonetheless, the conference would have benefitted if such a survey had been presented to set the stage for the ensuing discussions.

8. CONCLUSIONS

In summary, it appears that the following major conclusions can be drawn:

(1) This conference on high temperature problems in gas turbines resulted in a successful interchange of much valuable technical information regarding status on the design aspects of high temperature components, and the potential of new concepts in testing, cooling, design, materials and coating technology required to obtain further improvements in performance, cost, reliability and maintenance aspects of advanced engines. It is believed that NATO member nations participating in this meeting were able to develop a realistic assessment of the overall current state of the art, as well as the future potential approaches for the attainment of further increases in turbine inlet temperatures.

(2) There was agreement among the speakers and those who participated in the discussions that efficient utilization of the cooling air used to maintain proper metal temperatures is of paramount importance. Futhermore, it appears that further increases in turbine inlet temperatures, in the near term, will result from improvements in cooling concepts and configurations, combined with new or improved higher use temperature metals and coatings.

(3) Improved film cooling techniques with adequately developed design methods are seen as an important factor for future progress in high temperature turbines. It is believed that improved testing facilities, together with new measuring and analysis methods, can have considerable influence on further progress.

(4) Transpiration cooling of blades and vanes was shown to be very effective in maintaining low metal operating temperatures with very low cooling air flows. However, before the full performance benefits afforded by transpiration cooled blades can be realized, further improvements must be made on the allowable operating temperatures of porous materials. In addition, a critical review is required of the assumptions used in defining stage efficiency for cycles incorporating a transpiration cooled turbine. The methods presented at this conference appear to be overly pessimistic and in conflict with earlier published engine test results.

(5) Better understanding of the effect of engine-typical cooling air injection methods on turbine aerodynamics and overall engine performance is needed in order to focus research work on the reduction of performance losses.

(6) The selection of conference papers dealing with combustor-related problems appears to highlight the main fields for future development of this engine component: liner cooling techniques, application of ceramic materials, improved combustor analytical models and the use of alternative fuels with inherent engine design modifications. The last subject is believed to deserve additional attention in future conferences on high temperature turbines.

(7) Since the last AGARD meeting on high temperature turbines, progress has been demonstrated in fabrication technology for hot section components, as evidenced by the sophisticated film cooled blades, the diffusion bonded transpiration cooled blades, and the coated hardware examples presented in some papers during the course of this meeting.

(8) Much progress has been demonstrated in achieving the performance benefits of high technology in small gas turbines; however, further efforts are required to reach the higher performance levels demonstrated in high technology large engines.

(9) The successful interchange of much valuable technical information from the meeting, hopefully, will lead to some degree of standardization of terminology and, hence, result in an improvement of communications between the technical workers in this important, though somewhat specialized field.

9. RECOMMENDATIONS

(1) This meeting provided a measure of the progress made in technology of high temperature gas turbines since the last meeting, and provided useful and timely opportunities for the exchange of ideas and information on advanced concepts between the gas turbine specialists of the NATO countries.

It is recommended that a future meeting on high temperature turbines be held in 4-5 years. Using the present meeting as a base, it could evaluate the progress made in the intervening time. It appears that materials, cooling and coatings technology have progressed to the point that a significant step in operating temperatures of engines will take place in the next few years.

(2) A change in format of the meeting to include one or two half-day, round-table discussion sessions on a specific subject, problem area or theory, would enhance the technical interchange aspects of the meeting.

(3) As a final recommendation, it would be desirable, at a future assemblage of this eminent group of specialists, that a keynote overall survey paper be given by an engine manufacturer or government technical organization outlining the specific benefits in cycle performance or aircraft mission performance afforded by operating at high turbine inlet temperatures.

REFERENCES

References 1–40 are printed in AGARD Conference Proceedings 229

1. White, E.A.; Holland, M.J. — *Project Optimisation of Military Gas Turbines with Respect to Turbine Life*

2. Belaygue, G. — *Problèmes des Hautes Températures dans les Petites Turbomachines*

3. Freche, J.C.; Ault, G.M. — *Progress in Advanced High Temperature Turbine Materials, Coatings, and Technology*

4. Due, H.F.; Easterling, A.E.; Haas, J.E. — *The Status of Small, Cooled, Axial-Flow Turbines*

5. François, J.; Le Bot, Y.; Michard, J.; Deguest, P. — *Adaptation d'un Banc de Turbine aux Recherches pour les Hautes Températures*

6. Köhler, H.; Hennecke, D.K,; Pfaff, K.; Eggebrecht, R. — *Hot Cascade Test Results of Cooled Turbine Blades and their Application to Actual Engine Conditions*

7. Kühl, W. — *Investigations on the Local Heat Transfer Coefficient of a Convection Cooled Rotor Blade*

8. Kruse, H. — *Investigation on Temperature Distribution near Film-Cooled Airfoils*

9. Saryal, N.; Ghantous, I.N.; Çitçi, A. — *Erosion Prevention and Film Cooling on Vanes*

10. Bayley, F.J. — *Performance and Design of Transpiration-Cooled Turbine Blading*

11. Han, L.S.; Winget, L. — *The Influence of Transpiration Cooling on Turbine Blade Boundary Layer*

12. Morris, A.W.H.; Bullard, J.B.; Wigg, L.D. — *Experimental Evaluation of a Transpiration Cooled Nozzle Guide Vane*

13. Stuart-Mitchell, R.W.; Andries, J. — *Heat Transfer Characteristics of the Closed Thermosyphon System*

14. Owen, J.M. — *Heat Transfer from Turbine and Compressor Discs*

15. Buisson, M.; Gaillac, J.P.; Deroide, B. — *Revue des Techniques de Protection Thermique des Parois des Foyers Principaux et de Réchauffe des Turboréacteurs*

16. Winter, J.; Todd, H. — *Practical Solutions to the Cooling of Combustors Operating at High Temperatures*

17. Best, R. — *The Influence of Coolant Turbulence Intensity on Film Cooling Effectiveness*

18. Martorano, L.; Dini, D. — *High Temperature H_2-Air Variable Geometry Combustor and Turbine: Test Facility and Measurements*

19. Underwood, F.N.; Rusnak, J.P.; Ernst, R.C.; Petrino, E.A.; Russell, P.L. — *Low Frequency Combustion Instability in Augmentors*

20.	Bibring, H.	*Materiaux d'Avenir pour Turbines à Haute Température. Les Composites ONERA Face aux Problèmes d'Aubes*
21.	Ducati, U. Lecis Coccia, G. Cavalotti, P. Borile, F.	*High Temperature Corrosion of Ni-Base for Turbine Blade Alloys in Sulphate-Chloride Containing Environments*
22.	Galmiche, P.	*Protection d'Aubes Refroidies à Structure Interne Complexe*
23.	Davin, A. Drapier, J.M. Coutsouradis, D. Habraken, L.	*Cobalt-Base Alloys for Hot Corrosion Protective Coatings*
24.	Price. J.L. Gershon, I.J.	*Trends of Future Turbine Life Prediction; Time Phased Automated Analysis and Test Verification*
25.	Beckers, P. Sander, G. Hogge, M.	*Finite Element Analysis of Some Problems Arising in Cooled Turbine Blades*
26.	–	
27.	Sedgwick, G.	*Evaluation of a Ceramic Combustion Chamber for a Small Gas Turbine Engine*
28.	Louis, J.F.	*Systematic Studies of Heat Transfer and Film Cooling Effectiveness*
29.	McDonel, J.D. Eiswerth, J.E.	*Effects of Film Injection on Performance of a Cooled Turbine*
30.	Lawaczeck, O.	*The Influence of Jets of Cooling Air Exhausted from the Trailing Edges of a Supercritical Turbine Cascade on the Aerodynamic Data*
31.	Schultz, D.L. Jones, T.V. Oldfield, M.L.G. Daniels, L.C.	*A New Transient Cascade Facility for the Measurement of Heat Transfer Rates*
32.	Martin, B.W. Brown, A. Garrett, S.E.	*Heat Transfer to a PVD Rotor Blade at High Subsonic Passage Throat Mach Numbers*
33.	Le Bot, Y. Charpenel, M. Michard, P-J.	*Techniques de Mesure dans les Turbines à Hautes Températures*
34.	Ville, J.P. Richards, B.E.	*The Measurement of Film Cooling Effectiveness on Turbine Components in Short Duration Wind Tunnels*
35.	Ghezzi, U. Zizak, G. Coghe, A. Cignoli, F. Benecchi, S.	*Local Flame Temperature Measurements by Radiative Methods*
36.	Le Grivès, E. Nicolas, J.J.	*Methode Nouvelle de Calcul de l'Efficacité de Refroidissement des Aubes de Turbine par Film d'Air*
37.	Bayley, F.J. Milligan, R.W.	*The Effect of Free-Stream Turbulence upon Heat Transfer to Turbine Blading*
38.	Morris, W.D.	*Flow and Heat Transfer in Rotating Coolant Channels*
39.	Caprili, M. Lazzeretti, R.	*Calculation of Temperature Distribution in Discs and Cooling Flow in a Transient State*

40. Jones, W.P.
Clifford, W.C.
Priddin, C.H.
de Chair, R.

A Comparison between Predicted and Measured Species Concentrations and Velocities in a Research Combustor

REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's Reference	3. Further Reference	4. Security Classification of Document
	AGARD-AR-116	ISBN 92-835-1277-4	UNCLASSIFIED

5. Originator Advisory Group for Aerospace Research and Development
North Atlantic Treaty Organization
7 rue Ancelle, 92200 Neuilly sur Seine, France

6. Title TECHNICAL EVALUATION REPORT on the 50th Meeting of the PROPULSION AND ENERGETICS PANEL – A Symposium on HIGH-TEMPERATURE PROBLEMS IN GAS TURBINE ENGINES

7. Presented at

8. Author(s)	9. Date
R.Eggebrecht* and S.Lombardo†	March 1978

10. Author's Address		11. Pages
* MTU München GmbH 8000 München 50, Germany	† Curtiss-Wright Corp. Wood-Ridge, N.J., USA	18

12. Distribution Statement This document is distributed in accordance with AGARD policies and regulations, which are outlined on the Outside Back Covers of all AGARD publications.

13. Keywords/Descriptors

Gas turbine engines	Cooling	Design criteria
Heat resistant alloys	Combustion chambers	Heat resistant coatings
Heat transfer	Afterburners	

14. Abstract

This Technical Evaluation Report on the 50th PEP Symposium on "High-Temperature Problems in Gas Turbine Engines" contains a critical survey of the 37 papers presented, which are grouped according to the various subjects covered in this Symposium. (Progress of New Research and Development Test Facilities, Cooling Techniques and Heat Transfer Investigations, Effect of Turbine Cooling on Aerodynamic Performance, Combustors and Afterburners, High Temperature Materials and Coatings, Overall Engine Design and Performance Aspects.) Conclusions are drawn and areas with high-priority future interest are marked.

The papers presented at the meeting, together with the discussions, are published as AGARD Conference Proceedings CP-229 "High-Temperature Problems in Gas Turbine Engines".

AGARD Advisory Report No.116
Advisory Group for Aerospace Research and Development, NATO
TECHNICAL EVALUATION REPORT on the 50th Meeting of the PROPULSION AND ENERGETICS PANEL – A Symposium on HIGH-TEMPERATURE PROBLEMS IN GAS TURBINE ENGINES
by R.Eggebrecht and S.Lombardo
Published March 1978
18 pages

This Technical Evaluation Report on the 50th PEP Symposium on "High-Temperature Problems in Gas Turbine Engines" contains a critical survey of the 37 papers presented, which are grouped according to the various subjects covered in this Symposium. (Progress

P.T.O.

AGARD-AR-116

Gas turbine engines
Heat resistant alloys
Heat transfer
Cooling
Combustion chambers
Afterburners
Design criteria
Heat resistant coatings

AGARD Advisory Report No.116
Advisory Group for Aerospace Research and Development, NATO
TECHNICAL EVALUATION REPORT on the 50th Meeting of the PROPULSION AND ENERGETICS PANEL – A Symposium on HIGH-TEMPERATURE PROBLEMS IN GAS TURBINE ENGINES
by R.Eggebrecht and S.Lombardo
Published March 1978
18 pages

This Technical Evaluation Report on the 50th PEP Symposium on "High-Temperature Problems in Gas Turbine Engines" contains a critical survey of the 37 papers presented, which are grouped according to the various subjects covered in this Symposium. (Progress

P.T.O.

AGARD-AR-116

Gas turbine engines
Heat resistant alloys
Heat transfer
Cooling
Combustion chambers
Afterburners
Design criteria
Heat resistant coatings

AGARD Advisory Report No.116
Advisory Group for Aerospace Research and Development, NATO
TECHNICAL EVALUATION REPORT on the 50th Meeting of the PROPULSION AND ENERGETICS PANEL – A Symposium on HIGH-TEMPERATURE PROBLEMS IN GAS TURBINE ENGINES
by R.Eggebrecht and S.Lombardo
Published March 1978
18 pages

This Technical Evaluation Report on the 50th PEP Symposium on "High-Temperature Problems in Gas Turbine Engines" contains a critical survey of the 37 papers presented, which are grouped according to the various subjects covered in this Symposium. (Progress

P.T.O.

AGARD-AR-116

Gas turbine engines
Heat resistant alloys
Heat transfer
Cooling
Combustion chambers
Afterburners
Design criteria
Heat resistant coatings

AGARD Advisory Report No.116
Advisory Group for Aerospace Research and Development, NATO
TECHNICAL EVALUATION REPORT on the 50th Meeting of the PROPULSION AND ENERGETICS PANEL – A Symposium on HIGH-TEMPERATURE PROBLEMS IN GAS TURBINE ENGINES
by R.Eggebrecht and S.Lombardo
Published March 1978
18 pages

This Technical Evaluation Report on the 50th PEP Symposium on "High-Temperature Problems in Gas Turbine Engines" contains a critical survey of the 37 papers presented, which are grouped according to the various subjects covered in this Symposium. (Progress

P.T.O.

AGARD-AR-116

Gas turbine engines
Heat resistant alloys
Heat transfer
Cooling
Combustion chambers
Afterburners
Design criteria
Heat resistant coatings

of New Research and Development Test Facilities, Cooling Techniques and Heat Transfer Investigations, Effect of Turbine Cooling on Aerodynamic Performance, Combustors and Afterburners, High Temperature Materials and Coatings, Overall Engine Design and Performance Aspects.) Conclusions are drawn and areas with high-priority future interest are marked.

The papers presented at the meeting, together with the discussions, are published as AGARD Conference Proceedings CP-229 "High-Temperature Problems in Gas Turbine Engines".

ISBN 92-835-1277-4

of New Research and Development Test Facilities, Cooling Techniques and Heat Transfer Investigations, Effect of Turbine Cooling on Aerodynamic Performance, Combustors and Afterburners, High Temperature Materials and Coatings, Overall Engine Design and Performance Aspects.) Conclusions are drawn and areas with high-priority future interest are marked.

The papers presented at the meeting, together with the discussions, are published as AGARD Conference Proceedings CP-229 "High-Temperature Problems in Gas Turbine Engines".

ISBN 92-835-1277-4

of New Research and Development Test Facilities, Cooling Techniques and Heat Transfer Investigations, Effect of Turbine Cooling on Aerodynamic Performance, Combustors and Afterburners, High Temperature Materials and Coatings, Overall Engine Design and Performance Aspects.) Conclusions are drawn and areas with high-priority future interest are marked.

The papers presented at the meeting, together with the discussions, are published as AGARD Conference Proceedings CP-229 "High-Temperature Problems in Gas Turbine Engines".

ISBN 92-835-1277-4

of New Research and Development Test Facilities, Cooling Techniques and Heat Transfer Investigations, Effect of Turbine Cooling on Aerodynamic Performance, Combustors and Afterburners, High Temperature Materials and Coatings, Overall Engine Design and Performance Aspects.) Conclusions are drawn and areas with high-priority future interest are marked.

The papers presented at the meeting, together with the discussions, are published as AGARD Conference Proceedings CP-229 "High-Temperature Problems in Gas Turbine Engines".

ISBN 92-835-1277-4

AGARD

NATO OTAN

7 RUE ANCELLE · 92200 NEUILLY-SUR-SEINE

FRANCE

Telephone 745.08.10 · Telex 610176

DISTRIBUTION OF UNCLASSIFIED AGARD PUBLICATIONS

AGARD does NOT hold stocks of AGARD publications at the above address for general distribution. Initial distribution of AGARD publications is made to AGARD Member Nations through the following National Distribution Centres. Further copies are sometimes available from these Centres, but if not may be purchased in Microfiche or Photocopy form from the Purchase Agencies listed below.

NATIONAL DISTRIBUTION CENTRES

BELGIUM
Coordonnateur AGARD – VSL
Etat-Major de la Force Aérienne
Quartier Reine Elisabeth
Rue d'Evere, 1140 Bruxelles

CANADA
Defence Scientific Information Service
Department of National Defence
Ottawa, Ontario K1A OZ2

DENMARK
Danish Defence Research Board
Østerbrogades Kaserne
Copenhagen Ø

FRANCE
O.N.E.R.A. (Direction)
29 Avenue de la Division Leclerc
92 Châtillon sous Bagneux

GERMANY
Zentralstelle für Luft- und Raumfahrt-
dokumentation und -information
c/o Fachinformationszentrum Energie,
Physik, Mathematik GmbH
Kernforschungszentrum
7514 Eggenstein-Leopoldshafen 2

GREECE
Hellenic Armed Forces Command
D Branch, Athens

ICELAND
Director of Aviation
c/o Flugrad
Reykjavik

ITALY
Aeronautica Militare
Ufficio del Delegato Nazionale all'AGARD
3, Piazzale Adenauer
Roma/EUR

LUXEMBOURG
See Belgium

NETHERLANDS
Netherlands Delegation to AGARD
National Aerospace Laboratory, NLR
P.O. Box 126
Delft

NORWAY
Norwegian Defence Research Establishment
Main Library
P.O. Box 25
N-2007 Kjeller

PORTUGAL
Direcção do Serviço de Material
da Forca Aerea
Rua da Escola Politecnica 42
Lisboa
Attn: AGARD National Delegate

TURKEY
Department of Research and Development (ARGE)
Ministry of National Defence, Ankara

UNITED KINGDOM
Defence Research Information Centre
Station Square House
St. Mary Cray
Orpington, Kent BR5 3RE

UNITED STATES
National Aeronautics and Space Administration (NASA)
Langley Field, Virginia 23365
Attn: Report Distribution and Storage Unit

THE UNITED STATES NATIONAL DISTRIBUTION CENTRE (NASA) DOES NOT HOLD STOCKS OF AGARD PUBLICATIONS, AND APPLICATIONS FOR COPIES SHOULD BE MADE DIRECT TO THE NATIONAL TECHNICAL INFORMATION SERVICE (NTIS) AT THE ADDRESS BELOW.

PURCHASE AGENCIES

Microfiche or Photocopy
National Technical
Information Service (NTIS)
5285 Port Royal Road
Springfield
Virginia 22151, USA

Microfiche
Space Documentation Service
European Space Agency
10, rue Mario Nikis
75015 Paris, France

Microfiche
Technology Reports
Centre (DTI)
Station Square House
St. Mary Cray
Orpington, Kent BR5 3RF
England

Requests for microfiche or photocopies of AGARD documents should include the AGARD serial number, title, author or editor, and publication date. Requests to NTIS should include the NASA accession report number. Full bibliographical references and abstracts of AGARD publications are given in the following journals:

Scientific and Technical Aerospace Reports (STAR)
published by NASA Scientific and Technical
Information Facility
Post Office Box 8757
Baltimore/Washington International Airport
Maryland 21240, USA

Government Reports Announcements (GRA)
published by the National Technical
Information Services, Springfield
Virginia 22151, USA

Printed by Technical Editing and Reproduction Ltd
Harford House, 7–9 Charlotte St, London W1P 1HD

ISBN 92-835-1277-4